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Recent Results of Searches for New Particles in CDF

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Abstract.
The CDF Collaboration has searched for new particles in 109 pb^{-1} integrated luminosity of $p\bar{p}$ collisions at the Tevatron. The lastest results are presented, including searches for leptoquarks, Higgs bosons, supersymmetric particles, and heavy stable charged particles.

1. Introduction

In the years 1992-1993, the CDF detector at Fermilab recorded data corresponding to about 20 pb^{-1} integrated luminosity of $p\bar{p}$ collisions at the Tevatron. This run, called Run 1A, was followed in 1993-1995 by Run 1B, in which roughly 90 pb^{-1} were recorded, for a total Run 1 integrated luminosity of 110 pb^{-1}. This large sample of data led to the discovery of the top quark [1], precision electroweak measurements, studies of b quark mesons, studies of quantum chromodynamics, and the search for new particles and phenomena beyond the standard model. This paper presents recent results on this latter topic, including the search for leptoquarks, charged and neutral Higgs bosons, supersymmetric processes leading to final states with photon, and the search for stable ehavy charged particles.

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The CDF detector is described in detail elsewhere [2]. Searches for new particles make use of its full range of features, particularly its excellent electron and muon triggering and identification, missing transverse energy determination, b-jet tagging, and hadronic tau lepton decay identification.

2. Leptoquarks

The two HERA experiments H1 and ZEUS have observed an excess of events, in high energy collisions of electrons and protons, having large Q^2 and large x [3]. These events have an electron and a hadronic jet in the final state, and the invariant mass of the electron-jet system is near 200 GeV/c^2. Among the possible interpretations for these events is the production of a first-generation leptoquark via electron-quark scattering in the s channel, with the subsequent decay of the leptoquark to an electron and a quark in the final state.

If such a leptoquark exists, it can be pair-produced at the Tevatron with a cross section of about 0.2 pb at a mass of 200 GeV/c^2. These events would have an electron, a positron, and two jets in the final state. The main background for such events is the production of a Z in conjunction with two (or more) jets, or Drell-Yan production of electron-positron pairs with two or more jets.

CDF has performed a search for such events, requiring two electrons with transverse energy E_T exceeding 25 GeV, and two jets, one of which must have E_T >15 GeV, and the other must have E_T >30 GeV. The scalar sum of the electron and positron E_T must be grater than 70 GeV, as must the scalar sum of the jet E_T. The electron-positron invariant mass must not lie in the range 76-106 GeV/c^2, in order to suppress the Z + jets background. Starting with the data collected with electron triggers, these selection criteria leave 12 events, with 14±2 expected from the background processes.

In each event there can be two possible e-jet pairings; that pair with the smaller mass difference ΔM_{ej} is chosen, where ΔM_{ej} is the difference in the two e-jet invariant masses. As a final requirement, since in leptoquark pair events the masses must be equal, the analysis demands that ΔM_{ej} be less than $0.2\times\bar{M}_{ej}$. This leaves three events, all at relatively low e-jet masses.[2] After all cuts one expects 6±2 events from background processes.

Figure 1 shows the 95% CL limit one obtains as a result, as a function of leptoquark mass, demanding that at each e-jet mass the events lie within $\pm3\sigma$ of that mass. The theoretical prediction of the leptoquark cross section [4] depends systematically on the choice of Q^2 scale; we consider the range from $0.5\times\bar{M}_{ej}$ to $2\times\bar{M}_{ej}$. A first-generation leptoquark of mass less

[2] One of these, remarkably, is the well-known "ee$\gamma\gamma$" event.

than 210 GeV/c^2 is excluded if the theoretical cross section is at least at the lower end of this range.

3. Higgs

Electroweak symmetry breaking requires the existence of a Higgs boson which gives mass to the fundamental fermions. In the minimal standard model there is one neutral scalar Higgs boson. In extensions to the standard model with two Higgs doublets, there are five Higgses, two of which are charged scalars, two of which are neutral scalars, and one of which is a neutral pseudoscalar.

In $p\bar{p}$ collisions at the Tevatron, the dominant neutral scalar Higgs production mode is via gluon-gluon fusion to a single Higgs. The huge background from QCD processes makes observation of the Higgs in this mode nearly impossible, even though the cross section is not small. The modes to which the Tevatron experiments are most sensitive are Higgs production in association with a Z or W boson. Together these modes have a cross section on the order of 1 pb for a Higgs of mass 100 GeV/c^2.

CDF has searched for WH and ZH production in two final states, the $q\bar{q}b\bar{b}$ mode and the $\ell\nu b\bar{b}$ modes. In the four-jet mode there is a large background due to multi-jet QCD processes. By selecting all 592 events with two b-tagged jets and two other jets, one can examine the distribution of invariant mass of the $b\bar{b}$ system and fit the spectrum to a combination of background and signal. This allows the extraction of the 95% CL limit on Higgs production cross section which appears in figure 3. This limit is a factor of more than twenty from the standard model prediction. With more data, better b-tagging, and better background rejection CDF might in the future be able to discover or rule out the Higgs in this mode.

The final state with a lepton, missing $\mathrm{E_T}$, and two b-quark jets suffers less background. Figure 2 shows the two-jet mass distribution for events passing the selection requirements, for the cases of one and two b jets tagged. The plot shows the observed spectrum compared with the expectation from W+jets and $t\bar{t}$ events. There is a slight excess; one observes 36 events in the single-tag case, where one expects 30$\pm$2 from standard model processes. The corresponding numbers for the double-tag case are 6 observed, and 3.0$\pm$0.6 expected from background. A Higgs signal would appear as an excess with a mass peak of width of about 15 GeV.

Figure 3 shows the limit from the $\ell\nu b\bar{b}$ search, along with the limits from the four-jet search. Here as well the present limits are more than an order of magnitude from the standard model prediction, and hopefully in the future one can improve these limits with more data and an improved detector.

As mentioned above, a charged Higgs boson arises in extensions to the standard model (such as supersymmetry) with two Higgs doublets. If the charged Higgs is less massive than the top quark, and if the parameter $\tan\beta$ (the ratio of the vacuum expectation values of the two Higgs doublets) is large, then the top can decay predominantly to the charged Higgs and a b quark. In this regime, the charged Higgs decays almost exclusively to $\tau\nu_\tau$. At the Tevatron, then, this gives rise to an apparent excess of $t\bar{t}$-like events in which the usual W decays to $\tau\nu_\tau$.

CDF has performed a search for such events by selecting those events with a hadronically decaying tau, two jets (one of which must be b-tagged), and a fourth object which can be either an e, μ, another hadronically decaying τ, or a third jet. There must be large missing $\mathrm{E_T}$, reflecting the presence of energetic neutrinos. This selects 6 events from 109 pb^{-1}. The dominant background is from W+jets events in which the hadronic jets fluctuate to "fake" a hadronically decaying tau.

If the $H^{\pm}$ mass is large, then the final state b jets from $t \to Hb$ can have small energy and not pass the jet identification $\mathrm{E_T}$ threshhold of 15 GeV. In such events, one would observe two hadronically decaying taus and large missing $\mathrm{E_T}$. By demanding two identified taus with $\mathrm{E_T}$ >30 GeV, not back-to-back in azimuth, one selects no events in the data (with about 1 expected from background).

Figure 4 shows the region of the m_H versus $\tan\beta$ plane excluded by the search. The left-hand plot shows the region excluded in one demands that the $t\bar{t}$ cross section increases as $\tan\beta$ increases in order to keep the $t \to Wb$ rate constant, and consistent with the measured value of 6.8 pb. The right-hand plot shows the region excluded if the cross section is 5.0 pb (the theoretical value [5]) or 7.5 pb.

4. Supersymmetry

It was pointed out as early as 1985 [6] that in certain regions of the parameter space of supersymmetry, the dominant decay mode of the next-to-lightest supersymmetric particle (NLSP) to the lightest (LSP) might be via a loop diagram involving a final state photon. For example, if the LSP is a neutralino (N_1) with significant higgsino content, the NLSP (the next-lightest neutralino, N_2) might decay via $N_2 \to \gamma N_1$ giving rise to an energetic photon in the final state.

Interest in such a scenario rekindled following the observation by CDF of the event shown in Figure 5. This remarkable event has four electromagnetic energy deposits, three of which lie in the central region. Two of these have no nearby charged tracks, consistent with the interpretation that they

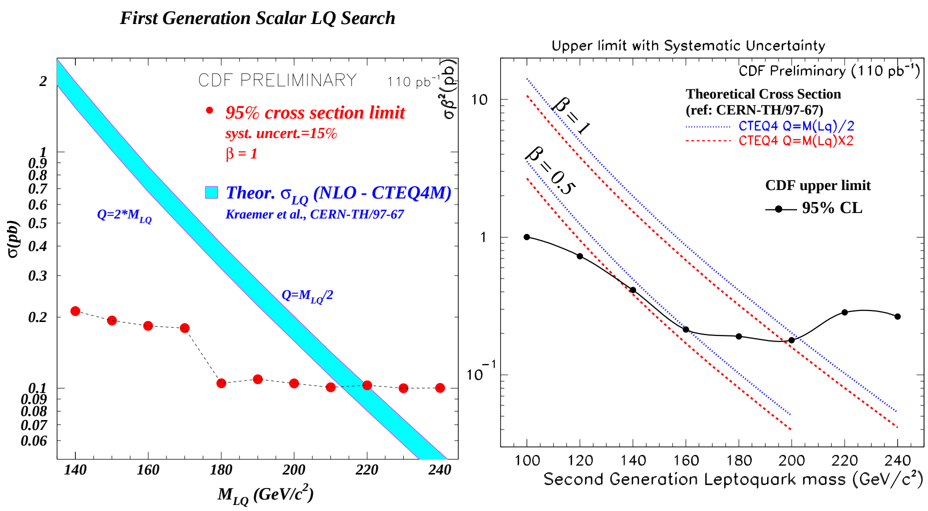

Figure 1. Limit, at 95% CL, on leptoquark cross section as a function of leptoquark mass for first-generation (left) and second-generation (right) leptoquarks.

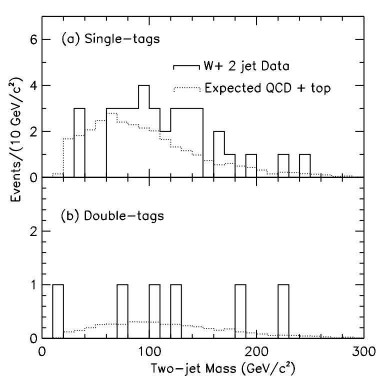

Figure 2. Distribution of two-jet mass in candidate events with a) one b-tagged jet and b) with two b-tagged jets. Solid histogram shows the observed events, and the dashed histogram shows the expectation from background.

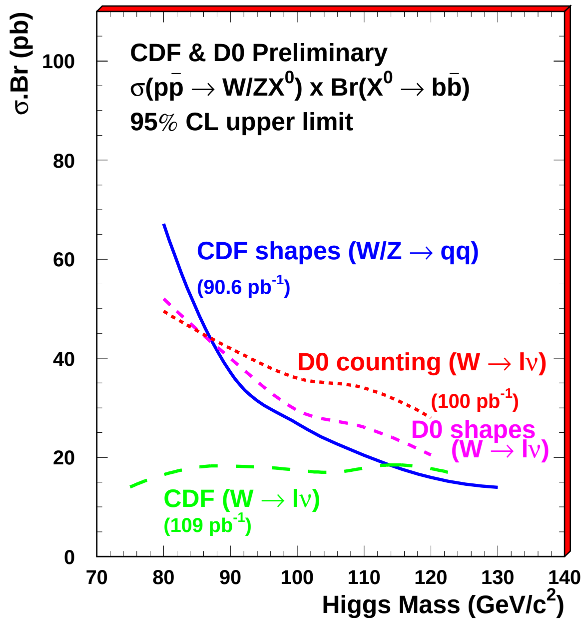

Figure 3. Cross section times branching ratio 95as a function of neutral Higgs mass for various searches.

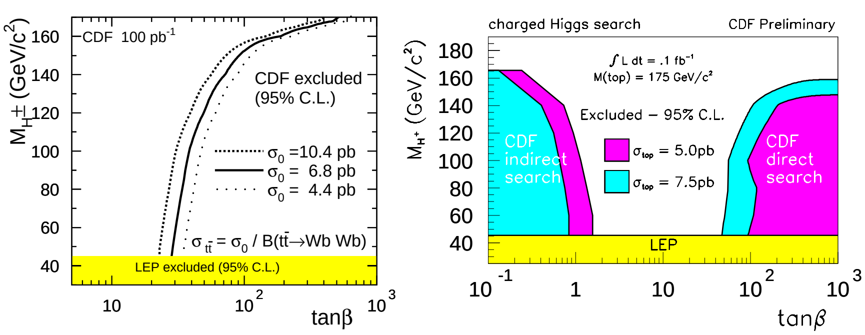

Figure 4. Regions in plane of m_{Higgs} versus $\tan\beta$ excluded by the searches, (left) allowing the $t\bar{t}$ cross section to increase with $\tan\beta$ so as to maintain consistency with the top quark discovery, and (right) for the searches at low and high $\tan\beta$ with constant top cross sections.

are photons. The other central deposit has a single high-p_T track associated with it; it passes all the standard selection criteria for electrons. The forward deposit, lying outside the tracking region of the CTC, nevertheless has three hits in the SVX which form a track pointing near the deposit. Thus this particle could be a positron, though such an interpretation is not iron-clad from a statistical standpoint. Perhaps most remarkably the event has over 50 GeV missing transverse energy.

The most likely standard model process which would give rise to an event with two electrons, two photons, and large missing transverse energy is $WW\gamma\gamma$ production with both W bosons decaying to $e\nu$. This is an unlikely explanation for two reasons. Firstly the cross section for this process is roughly 0.15 fb, to be multiplied by the branching ratio (1/81) and acceptance. The number of expected events (still under study) of this type is thus very small. Secondly, even if the cross section for such process were enhanced for some reason, there should, statistically, be very many more events in the decay modes from the other 79/81 of the branching ratio. Nevertheless, this is but one event out of roughly 10^{13} $p\bar{p}$ interactions and an *a posteriori* estimate of probabilities remains fraught with interpretational problems. Only future data will be able to definitively answer the question of whether a standard model interpretation for this event exists.

If the standard model explanation for this event is not correct, various supersymmetric interpretations might account for it, but predict other observable consequences. For example, as pointed out by Ambrosianio et al. [8] the event could arise from selectron pair production, with the decay $\tilde{e} \rightarrow eN_2$, with $N_2 \rightarrow N_1\gamma$. In the region of parameter space where one expects on the order of one event, one would also expect other events with two photons and missing $\mathrm{E_T}$ from other SUSY processes.

CDF has performed a search with the sample of all events having two identified photons, each having $\mathrm{E_T} > 25$ GeV. The photons in this sample come mainly from fakes due to either energetic π^0's or predominantly electromagnetic jets which flutuate to pass the photon requirements. One can then examine the missing $\mathrm{E_T}$ distribution of the sample and attempt to determine whether there is an excess of suh events with large missing $\mathrm{E_T}$. The distribution appears in the left-hand plot of Figure 6, in comparison with the distribution from $Z \rightarrow ee$ events, which should have similar biases. Only the event from Figure 5 has $\not{E}_\mathrm{T}$ in excess of 30 GeV. The plot also shows the expectation from one parameter set from the model of Ambrosanio, *et al.*; one would expect many more events if that model obtained. Work is underway to define and express the region of parameter space ruled out by this search.

A related search, also suggested by the same authors, looks for events with a photon, a $b-$tagged jet, and missing $\mathrm{E_T}$, coming from the associated production of a chargino and neutralino decaying to a light stop quark:

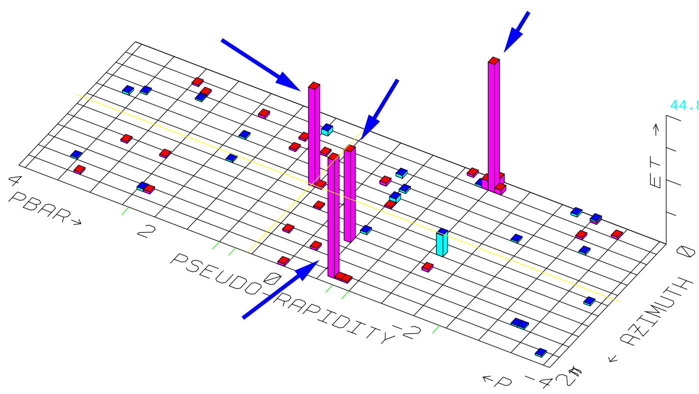

Figure 5. Event display of the e"e"$\gamma\gamma$ event recorded in Run 1B.

$C_i N_2 \to \tilde{t} b \gamma N_1$. Demanding the presence of a photon with $\mathrm{E_T} > 25$ GeV, a b-tagged jet, and 40 GeV missing $\mathrm{E_T}$ selects two events; relaxing the $\not\!\!E_{\mathrm{T}}$ cut to 20 GeV selects 98 events, with roughly 80±9 and 89±22 predicted from two independent background estimates.

The right-hand plot of Figure 6 shows the missing $\mathrm{E_T}$ spectrum of the accepted events, again with comparison to the background and model prediction (scaled up by ×100). Again, that particular point in parameter space can be ruled out at 95% CL. In the future this limit will be expressed in a model-independent way which will allow model builders to compare their predictions with this result.

5. Stable Heavy Charged Particles

In various scenarios, the possibility of new, massive, and relatively stable ($\tau > 10^{-8}$ sec) charged particle arises. For example, in supersymmetry the decay of the chargino to the LSP might be suppressed giving rise to a massive, stable charged particle.

Such particles would ionize in the tracking volume at a potentially very large rate due to their low velocity. In CDF, the specific ionization (dE/dx) can be measured with both the SVX and the CTC. Figure 7 shows the mean dE/dx as a function of charged particle p_T, with the Bethe-Block prediction

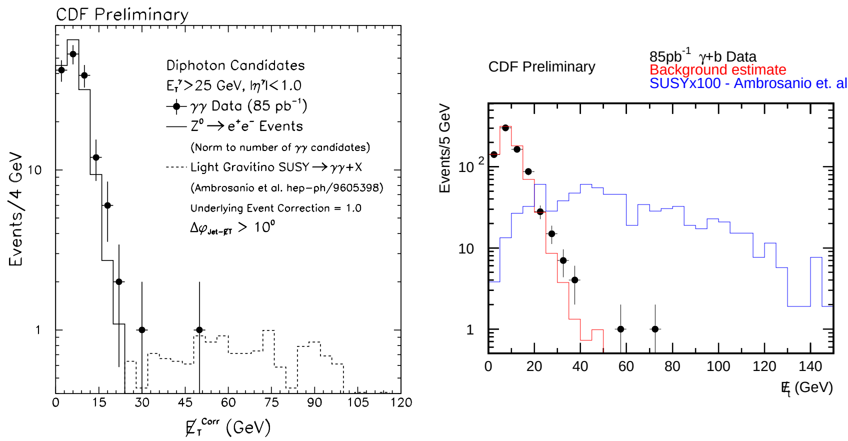

Figure 6. Distribution of missing $\mathrm{E_T}$ in (left) all events with two final-state photons and (right) events with a photon, a b-tagged jet, and missing $\mathrm{E_T}$.

superimposed. (Note the smaller relativistic rise in the case of the SVX due to the density effect.)

Measuring the p_T and dE/dx of a charged particle gives an estimate of its mass. In the analysis, one seeks charged tracks coming from a new massive, stable, fourth-generation quark, which hadronizes to a "meson" and travels through the tracking detectors, and deposits its energy in the hadron calorimeter. Such a particle would ionize more heavily than ordinary hadrons produced in hadronic interactions due to its low velocity.

In this analysis, one selects tracks from the events recorded with muon triggers, and demands that the track has sufficient hit information in the CTC and SVX to ensure reliable dE/dx information. The track must have a momentum of at least 30 GeV/c. One then selects "slow" particles by requiring $\beta\gamma < 0.85$. A tighter selection of $\beta\gamma < 0.70$ provides better background rejection for improved sensitivity at lower masses.

The left-hand plot in figure 8 shows the distribution of the estimated particle masses using tracks passing the final selection, in comaprison with the distribution expcected from background. The background comes mainly from tracks formed from particles whose trajectories overlapped.

To set limits on a heavy stable quark, one searches in bins of mass with a lower mass cut of -40%, correspondng to roughly -2σ. The right-hand plot of figure 8 shows the 95% CL limit on the cross section for this particle;

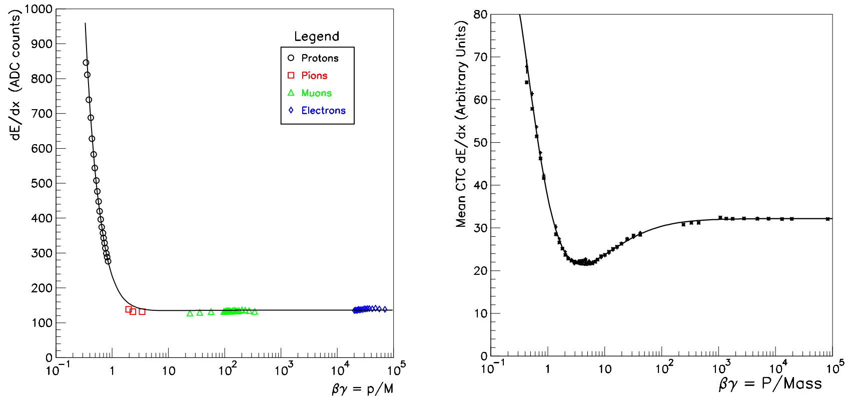

Figure 7. Average dE/dx as a function of track p_T for the SVX (left) and CTC (right).

the mass of a charge-1/3 quark must be greater than 195 GeV/c^2, and that of a charge-2/3 quark must exceed 220 GeV/c^2.

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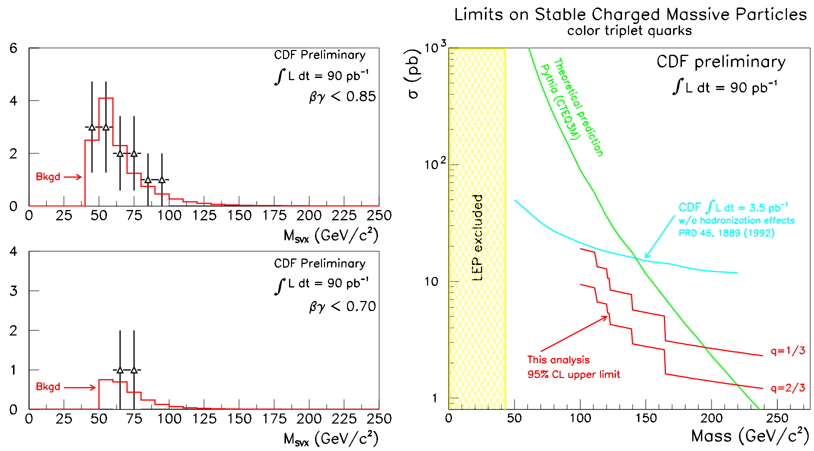

Figure 8. Distribution of mass (left) of selected tracks from the sample, and the 95% cross section limit as a function of the mass of a heavy stable quark.

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